Searches for Heavy Stable Charged Particles at the LHC

Loïc Quertenmont on behalf of CMS and ATLAS

12 November 2015
What are we talking about?

Appears in many scenarios and in various forms....

<table>
<thead>
<tr>
<th>SMP</th>
<th>LSP</th>
<th>Scenario</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{t}_1$</td>
<td>$\tilde{X}^0_1$</td>
<td>MSSM</td>
<td>$\tilde{t}<em>1$ mass (determined by $m^2</em>{\tilde{t}_{L,R}}, \mu, \tan \beta$, and $A_t$) close to $\tilde{X}^0_1$ mass.</td>
</tr>
<tr>
<td>$\tilde{G}$</td>
<td></td>
<td>GMSB</td>
<td>Large $N$, small $M$, and/or large $\tan \beta$.</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td></td>
<td>GMSB</td>
<td>No detailed phenomenology studies, see [23].</td>
</tr>
<tr>
<td>$\tilde{t}_1$</td>
<td></td>
<td>MSSM</td>
<td>Small $m_{\tilde{t}_{L,R}}$ and/or large $\tan \beta$ and/or very large $A_t$.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AMSB</td>
<td>Small $m_{\tilde{t}_0}$, large $\tan \beta$.</td>
</tr>
<tr>
<td>$\tilde{G}$</td>
<td></td>
<td>GMSB</td>
<td>$\tilde{G}$ NLSP (see above), $\tilde{G}$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan \beta$ and $\mu$.</td>
</tr>
<tr>
<td>$\tilde{t}_1$</td>
<td></td>
<td>$\tilde{g}$ MSB</td>
<td>$\tilde{t}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.</td>
</tr>
<tr>
<td>$\tilde{X}^+_1$</td>
<td>$\tilde{X}^0_1$</td>
<td>MSSM</td>
<td>$m_{\tilde{X}^+<em>1} - m</em>{\tilde{X}^0_1} \lesssim m_{\tilde{\tau}<em>1}$. Very large $M</em>{1,2} \gtrsim 2$ TeV $\gg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AMSB</td>
<td>$M_1 &gt; M_2$ natural, $m_{\tilde{t}_0}$ not too small. See MSSM above.</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>$\tilde{X}^0_1$</td>
<td>MSSM</td>
<td>Very large $m_{\tilde{g}}^2 \gg M_3$, e.g. split SUSY.</td>
</tr>
<tr>
<td>$\tilde{G}$</td>
<td></td>
<td>GMSB</td>
<td>SUSY GUT extensions [25–27].</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td></td>
<td>MSSM</td>
<td>Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{\text{GS}} = -3$.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GMSB</td>
<td>SUSY GUT extensions [25–29].</td>
</tr>
<tr>
<td>$\tilde{t}_1$</td>
<td>$\tilde{X}^0_1$</td>
<td>MSSM</td>
<td>Non-universal squark and gaugino masses. Small $m_{\tilde{q}}^2$ and $M_3$, small $\tan \beta$, large $A_t$.</td>
</tr>
<tr>
<td>$\tilde{b}_1$</td>
<td></td>
<td>Small $m_{\tilde{b}}^2$ and $M_3$, large $\tan \beta$ and/or large $A_b \gg A_t$.</td>
<td></td>
</tr>
</tbody>
</table>

**SUSY**

**EXOTIC**

<table>
<thead>
<tr>
<th>$Q_{\text{cm}}$</th>
<th>$C_{\text{QCD}}$</th>
<th>$S$</th>
<th>Model(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8</td>
<td>1</td>
<td>Universal Extra Dimensions (KK gluon)</td>
</tr>
<tr>
<td>$\pm 1$</td>
<td>1</td>
<td>$\frac{1}{2}$</td>
<td>Universal Extra Dimensions (KK lepton)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fat Higgs with a fat top ($\psi$ fermions)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4th generation (chiral) fermions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mirror and/or vector-like fermions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fat Higgs with a fat top ($\psi$ scalars)</td>
</tr>
<tr>
<td>$\pm \frac{4}{3}$</td>
<td>3</td>
<td>$\frac{1}{2}$</td>
<td>Warped Extra Dimensions with GUT parity (XY gaugino)</td>
</tr>
<tr>
<td>$-\frac{1}{3}$</td>
<td>3</td>
<td>$\frac{1}{3}$</td>
<td>5D Dynamical SUSY-breaking (xyon)</td>
</tr>
<tr>
<td>$\epsilon &lt; 1$</td>
<td>1</td>
<td>$\frac{1}{2}$</td>
<td>Universal Extra Dimensions (KK down, KK up)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4th generation (chiral) fermions</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>Mirror and/or vector-like fermions</td>
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<td></td>
<td></td>
<td></td>
<td>Warped Extra Dimensions with GUT parity (XY gaugino)</td>
</tr>
</tbody>
</table>

+++ other more exotic models/particles (monopoles, quirks, dyons, etc.)

**arXiv:hep-ph/0611040 Fairbairn et al.**
A rich phenomenology, dictating the experimental signature

- Heavy
- Stable
- Charged
What are we talking about?

A rich phenomenology, dictating the experimental signature

- **Heavy**
  Slow particle $\rightarrow \beta < 1$

- **Stable**

- **Charged**
A rich phenomenology, dictating the experimental signature

- **Heavy**
  - Slow particle $\rightarrow \beta < 1$

- **Stable $\rightarrow$ Long-lived**
  1) Reach the tracker $\rightarrow c\tau > O(0.1)\,m$
  2) Escape the detector $\rightarrow c\tau > O(10)\,m$
  3) Stop in $\rightarrow$ Asynchronous decay $\rightarrow c\tau > O(100)\,m$

- **Charged**
A rich phenomenology, dictating the experimental signature

- **Heavy**
  - Slow particle $\rightarrow \beta<1$

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  3) Stop in $\rightarrow$ Asynchronous decay $\rightarrow c\tau > O(100)\text{m}$

- **Charged**
  - Electric $\rightarrow$ lepton-like
    - $|Q|<e$, $|Q|<e$, $|Q|=e$, $|Q|>e$, $|Q|>>e$
  - Color $\rightarrow$ hadron-like $\rightarrow$ R-hadron properties ?!
    - (gluinoball, charge flip, interaction w/ matter, etc.)
  - Magnetic $\rightarrow$ monopoles, dyons
  - Exotic $\rightarrow$ quirks, …
A rich phenomenology, dictating the experimental signature

- **Heavy**
  - Slow particle $\rightarrow \beta<1$

- **Stable $\rightarrow$ Long-lived**
  1) Reach the tracker $\rightarrow c\tau > O(0.1)m$
  2) Escape the detector $\rightarrow c\tau > O(10)m$
  3) Stop in $\rightarrow$ Asynchronous decay $\rightarrow c\tau > O(100)m$

- **Charged**
  - Electric $\rightarrow$ lepton-like $|Q|<<e$, $|Q|<e$, $|Q|=e$, $|Q|>e$, $|Q|>>e$
  - Color $\rightarrow$ hadron-like $\rightarrow$ R-hadron properties ?!
    (gluinoball, charge flip, interaction w/ matter, etc.)
  - Magnetic $\rightarrow$ monopoles, dyons
  - Exotic $\rightarrow$ quirks, …

Terminology : HSCP=SMP=ChaMP=CmLLP=…
Experimental Signature

**IONIZING**

\[ \frac{dE}{dx} \]

\[ \frac{dE}{dx} \approx Q^2 \left( \frac{A}{\beta^2} + B \right) \text{ for } \beta \ll 1 \]

Magnetic charge \( g_D \rightarrow Q \sim 68.5e \)

**SLOW**

**Time Of Flight**

\[ 1/\beta = 1 + \frac{c\delta_t}{L} \]

with \( \delta_t = \text{delay} \)

\[ \beta \text{ resolution improves with time resolution } (\delta t) \]

\[ \text{and with lever arm } (L) \]

\[ dE/dx \text{ resolution improves with } \#\text{layers, sensor thickness and readout} \]
Experimental Signature

\[ \frac{dE}{dx} \approx \frac{Q^2}{\beta^2} \left( A + B \right) \text{ for } \beta << 1 \]

Magnetic charge \( g_D \rightarrow Q \sim 68.5e \)

**IONIZING**

\[ \text{dE/dx} \]

**SLOW**

Time Of Flight

\[ 1/\beta = 1 + \frac{c\delta t}{L} \]

with \( \delta t = \text{delay} \)

**STOPPED**

Decay asynchronously w.r.t LHC bunch

If dE/dx is (high) comparable to the kinetic energy
The particle may stop in the detector and decay later

\[ l_h (\text{MeV/cm}) \]

\[ p (\text{GeV/c}) \]

\[ \beta \text{ resolution improves with time resolution (} \delta t \text{) and with lever arm (L)} \]

\[ \beta \text{ resolution improves with } \# \text{layers, sensor thickness and readout} \]
ATLAS/CMS Detectors for HSCP

Time of Flight

Muon Chambers
DT + CSC

Muon Chambers
MDT + RPC

Calorimeter
ATLAS/CMS Detectors for HSCP

**dE/dx**

- Calorimeter
- Pixel tracker
- Strip tracker
- Muon Chambers
- DT + CSC

**Time of Flight**

- Calorimeter
- Muon Chambers
- MDT + RPC
- Pixel tracker
- Calorimeter
**ATLAS/CMS Detectors for HSCP**

**dE/dx**

- **Calorimeter**
- **Pixel tracker**
- **Strip tracker**
- **Muon Chambers**
- **DT + CSC**

**Time of Flight**

- **MDT**
- **Pixel tracker**
- **TRT**
- **Calorimeter**
- **Muon Chambers**
- **MDT + RPC**

* = only if $dE/dx \gg O(1) \text{ GeV}$

* = only in special stream
• R-Hadron charge can flip due to nuclear interaction
• Many possible R-Hadron interaction models → some predicts that flipping to neutral is more likely
• Gluino ball fraction (f) is also unknown (even if 10% in pythia)
ATLAS/CMS Searches

* = apply to $g_D \neq 0$

\[ \text{R-Hadron ?} \]

\[ \begin{align*}
\text{Q/g_d charge ?} \\
|Q| < 1 & \quad |Q| > 1^* \\
|Q| = 1 \\
\end{align*} \]

\[ \text{Stopped in ?} \]

\[ \pm \rightarrow \text{Charge ?} \rightarrow 0 \]
ATLAS/CMS Searches

*= apply to gD ≠ 0

R-Hadron ?

Q/gd charge ?

|Q|<1

|Q|<1/2

|Q|<=1

|Q|<1

|Q|<<1

|Q|<1

|Q|>1*

|Q|>1*

|Q|><1

|Q|>1*

|Q|>8

|Q|=1

|Q|=1

&darrow; &dagger; 0

± &darrow; ± &darrow; 0

± &darrow; ± 0 &darrow; 0

Stopped in ?

Charge ?

±

± &darrow; ± &darrow; 0

± &darrow; ± 0 &darrow; 0
ATLAS/CMS Searches

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\begin{itemize}
  \item \(N = \) apply to \(g_\text{D} \neq 0\)
\end{itemize}

\textbf{R-Hadron ?}

\begin{itemize}
  \item \(|Q/g_d| \text{ charge?} \)
  \begin{itemize}
    \item \(|Q| < 1\)
    \begin{itemize}
      \item \(|Q| \sim 1/2\)
      \item \(|Q| < 1\)
    \end{itemize}
    \item \(|Q| > 1\)
    \begin{itemize}
      \item \(|Q| > 1\)
      \item \(|Q| < 8\)
    \end{itemize}
    \item \(|Q| = 1\)
  \end{itemize}
  \item \(|Q| > 1\)
  \begin{itemize}
    \item \(|Q| > 1\)
    \item \(|Q| < 8\)
  \end{itemize}
  \item \(|Q| = 1\)
\end{itemize}

\textbf{Stopped in ?}

\begin{itemize}
  \item \(\pm\)
  \begin{itemize}
    \item \(\pm\)
    \item \(\pm \rightarrow 0\)
  \end{itemize}
  \item \(0\)
  \begin{itemize}
    \item \(0\)
    \item \(0 \rightarrow 0\)
  \end{itemize}
\end{itemize}

* CMS : TK
arXiv:1305.0491
\(pT + dEdx\)

\begin{itemize}
  \item Not covered
  \item But proposal for LHC exp.
arXiv:1410.6816
\end{itemize}
Selected Results on: $Q<1$

**The search in a nutshell**

- **Challenges:**
  - Small energy loss $\rightarrow$ LHC detectors and DAQ designed for $Q=1$
  - Out-of-time particles (cosmics/ghost) also lead to low $dE/dx$
- **Advantage:**
  - Tracking: high reco $p_T (=p_{T_{\text{True}}}/Q)$

**signature**

**Background (ABCD)**

**Limits**

12/11/2015 - Searches for HSCP at the LHC
ATLAS/CMS Searches

\[= \text{apply to } g_D \neq 0\]

\[\text{R-Hadron?} \quad \begin{cases} \text{no} & \text{Q/g}_d \text{ charge?} \\ \text{yes} & \text{Stopped in?} \end{cases}\]

\[|Q| < 1 \quad |Q| > 1^* \quad |Q| = 1\]

\[|Q| \sim 1/2 \quad |Q| < 1 \quad |Q| > 1^* \quad |Q| < 8 \quad |Q| = 1\]

\[\text{CMS: TK} \quad \text{arXiv:1305.0491} \quad \text{pT + dEdx}\]

\[\text{Not covered But proposal for LHC exp.} \quad \text{arXiv:1410.6816}\]
ATLAS/CMS Searches

*= apply to g_D≠0

R-Hadron ?

Q/g_d charge ?

|Q|<1

|Q|~1/2

|Q|<1/2

|Q|<<1

|Q|>>1*

|Q|>1*

|Q|<8

|Q|=1

|Q|=1

±

± → ±

± → 0

0 → ±

0 → 0

Stopped in ?

CMS : TK
arXiv:1305.0491
pT + dEdx

CMS : TK+MS
arXiv:1305.0491
dEdx + TOF
ATLAS:
arXiv:1504.04188
dEdx PIX,TRT,MDT

Not covered
But proposal
for LHC exp.
arXiv:1410.6816

ATLAS: TRT+EM
arXiv1509.08059
10<Q<60 & 0.5<g_D<1.5
arXiv1102.0459
6<Q<17
Searches for HSCP at the LHC

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Selected Results on: \(1 < Q < 10\)

### The search in a nutshell

**Challenges:**

- Tracking: smaller reco pT (\(\frac{p_T}{Q}\)) → trigger & background rate

**Solutions:**

- Requires it to reach MS (many redundant measurements dE/dx or TOF)
- Keep track pT threshold as low as possible (40GeV)

![Graphs showing comparable limits between CMS and ATLAS](image)
Selected Results on: \( Q \gg 1 \) or \( g_D \neq 0 \)

The search in a nutshell

- **Challenges:**
  - Tracking: small reco pT (=pT_{\text{True}} / Q) or track bending for \( g_D \neq 0 \)
  - Huge energy loss: not reach outer detector (+ possible DAQ issues)
- **Solutions:** Dedicated trigger + no tracking + only inner detectors (TRT and EM)
ATLAS/CMS Searches

* = apply to $g_D \neq 0$

R-Hadron ?

Q/g_d charge ?

$|Q|<1$

$|Q|>1^*$

$|Q|=1$

$|Q|\sim 1/2$

$|Q|<<1$

$|Q|>1^*$

$|Q|<8$

$|Q|=1$

CMS : TK
arXiv:1305.0491
$p_T + dEdx$

CMS : TK+MS
arXiv:1305.0491
dEdx + TOF

ATLAS:
arXiv:1504.04188
dEdx PIX,TRT,MDT

Stopped in ?

$\pm$

Charge ?

$\pm \rightarrow \pm$

$\pm \rightarrow 0$

$0 \rightarrow \pm$

$0 \rightarrow 0$

Not covered
But proposal for LHC exp.
arXiv:1410.6816

12/11/2015 - Searches for HSCP at the LHC

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ATLAS/CMS Searches

* = apply to $g_D\neq 0$

**R-Hadron ?**

- **Q/g_d charge ?**
  - |Q|<1
    - |Q|~1/2
      - CMS: TK
        - arXiv:1305.0491
        - $pT + dEdx$
  - |Q|<<1
    - CMS: TK+MS
      - arXiv:1305.0491
      - $dEdx + TOF$
      - ATLAS:
        - arXiv:1504.04188
        - $dEdx$ PIX, TRT, MDT
  - |Q|>>1*
    - ATLAS: TRT+EM
      - arXiv:1509.08059
      - 10<Q<60 & 0.5<g_D<1.5
      - arXiv:1102.0459
      - 6<Q<17
  - |Q|>8
    - Not covered
      - But proposal for LHC exp.
        - arXiv:1410.6816
    - CMS: CALO
      - arXiv:1501.05603
      - ATLAS: CALO
        - arXiv:1310.6584
  - |Q|=1
    - CMS: CALO
      - arXiv:1501.05603
      - ATLAS: CALO
        - arXiv:1310.6584
  - |Q|=1
    - CMS: CALO
      - arXiv:1501.05603
      - ATLAS: CALO
        - arXiv:1310.6584

**Stopped in ?**

- ±
  - Charge ?
    - 0
      - ± → ±
      - ± → 0
      - 0 → ±
      - 0 → 0

Selected Results on: Stopped HSCP

The search in a nutshell

- Signature: Energetic jet w/o pp collisions
- Backgrounds: cosmics, beam halo, det. noise

CMS Simulation

Stopped gluino decay
\( m_{\tilde{g}} = 300 \text{ GeV/c}^2 \)
\( m_{\tilde{g}^0} = 200 \text{ GeV/c}^2 \)

The CMS and ATLAS limits for gluinos and sbottoms with various decay channels and masses are presented. The CMS data includes observed and expected limits, while ATLAS shows limits on the decay lifetimes and masses.
ATLAS/CMS Searches

R-Hadron ?

no

Q/g_d charge ?

|Q|<1

|Q|=1

|Q|>1*

|Q|<<1

|Q|>>1*

|Q|<8

Stopped in ?

|±| ≤ 1

|±| ≥ 1

|±|<1

|±|>>1

|±|<8

|±|=1

© = apply to g_D≠0

CMS : TK
arXiv:1305.0491
pT + dEdx

CMS : TK+MS
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ATLAS:
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arXiv:1310.6584

not covered
But proposal for LHC exp.
arXiv:1410.6816

|±| → ±

|±| → 0

0→ ±

0→ 0

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**ATLAS/CMS Searches**

$*=\text{apply to } g_D \neq 0$

- **Q/g_d charge?**
  - $|Q|<1$
  - $|Q|>1^*$
  - $|Q|=1$
  - $|Q|\approx 1/2$
  - $|Q|<1$
  - $|Q|>1^*$
  - $|Q|<8$
  - $|Q|=1$

  - **CMS: TK**
    - arXiv:1305.0491
    - $p_T + dEdx$

  - **CMS: TK+MS**
    - arXiv:1305.0491
    - $dEdx + TOF$
    
      - **ATLAS:**
        - arXiv:1504.04188
        - $dEdx$ PIX,TRT,MDT

  - **ATLAS: TRT+EM**
    - arXiv:1509.08059
    - 10<Q<60 & 0.5<g_D<1.5
    
      - arXiv:1102.0459
    - 6<Q<17

- **R-Hadron?**
  - **Stopped in?**
    - ±
    - Charge? → 0
    - ± → ±
    - ± → 0
    - 0 → ±
    - 0 → 0

  - **CMS: CALO**
    - arXiv:1501.05603

  - **ATLAS: CALO**
    - arXiv:1310.6584

**Not covered**

**But proposal for LHC exp.**

- arXiv:1410.6816

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12/11/2015 - Searches for HSCP at the LHC

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Selected Results: Regular ($\pm \to \pm$) HSCP

- Very similar approach used by ATLAS and CMS
- Trigger: Muon OR MET
- Variables: $p_T$ (tracker), $dE/dx$ (inner detector) and TOF (Muon System)
- Background prediction based on ABCD and predicted mass spectrum from pdf
- Main difference: ATLAS has a 2 HSCP/event category not considered by CMS
Selected Results: **R-Hadrons** (±→0)

- Search almost identical to the R-Hadron (±→±) search
- Differences are:
  - Trigger efficiency is dominated by MET component
  - TOF measurements from the MS are dropped
  - CMS also considered pessimistic model where Prob(±→0) is ~100%
**ATLAS/CMS Searches**

- **R-Hadron?**
  - **Q/g_d charge?**
    - |Q|<1
      - |Q|~1/2
        - CMS: TK
          - arXiv:1305.0491
            - pT + dEdx
      - |Q|<<1
        - CMS: TK+MS
          - arXiv:1305.0491
            - dEdx + TOF
          - ATLAS: TRT+EM
            - arXiv:1509.08059
              - 10<Q<60 & 0.5<gD<1.5
            - arXiv:1102.0459
              - 6<Q<17
      - |Q|>>1*
        - CMS: TK+MS
          - arXiv:1305.0491
          - pT + dEdx (+ TOF)
          - ATLAS: PIX+CALO+(MDT/RPC)
            - arXiv:1411.6795
            - pT + dEdx (+ TOF)
      - |Q|>1*
        - CMS: TK+MS
          - arXiv:1305.0491
          - pT + dEdx (+ TOF)
          - ATLAS: PIX+CALO+(MDT/RPC)
            - arXiv:1411.6795
            - pT + dEdx (+ TOF)
      - |Q|=1
        - ATLAS: TRT+EM
          - arXiv:1509.08059
          - 10<Q<60 & 0.5<gD<1.5
        - arXiv:1102.0459
          - 6<Q<17
      - |Q|<8
    - |Q|>1*
      - CMS: TK+MS
        - arXiv:1305.0491
        - pT + dEdx (+ TOF)
        - ATLAS: PIX+CALO+(MDT/RPC)
          - arXiv:1411.6795
          - pT + dEdx (+ TOF)

- **Stopped in?**
  - ±
    - Charge? → 0
  - ± → ±
  - ± → 0
  - 0 → ±
  - 0 → 0

* = apply to gD≠0

---

12/11/2015 - Searches for HSCP at the LHC

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ATLAS/CMS Searches

\[ \frac{Q}{g_d} \text{ charge?} \]

- \(|Q| < 1\)
  - \(|Q| \approx 1/2\)
  - \(|Q| << 1\)
  - \(|Q| < 1\)
  - \(|Q| >> 1\)

- \(|Q| > 1^*\)
  - \(|Q| > 1^*\)
  - \(|Q| > 8\)
  - \(|Q| = 1\)

- \(|Q| = 1\)
  - \(|Q| = 1\)
  - \(|Q| = 1\)
  - \(|Q| = 1\)

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- \(|Q| = 1\)
  - \(|Q| = 1\)

- \(|Q| = 1\)
  - \(|Q| = 1\)

- \(|Q| = 1\)
  - \(|Q| = 1\)


R-Hadron?

- yes
  - Stopped in?
    - yes
      - Covered by usual SUSY MET / Mono-X searches
    - no
      - Charge?
        - yes
          - 0
          - 0
        - no
          - \(|Q|\)\to0
          - \(|Q|\)\to0

\[ \frac{Q}{g_d} \text{ charge?} \]

- \(|Q| < 1\)
  - CMS: TK
    - \(pT + dEdx\)
    - \(arXiv:1305.0491\)
    - CMS: TK+MS
      - \(pT + dEdx + TOF\)
      - \(arXiv:1305.0491\)
      - \(arXiv:1504.04188\)

- CMS: TK+MS
  - \(pT + dEdx (+ TOF)\)
  - \(arXiv:1411.6795\)

- ATLAS: TK+MS
  - \(pT + dEdx (+ TOF)\)
  - \(arXiv:1411.6795\)

- ATLAS: TRT+EM
  - \(arXiv:1509.08059\)
  - \(|10 < Q < 60 \text{ & } 0.5 < g_d < 1.5|\)
  - \(arXiv:1102.0459\)
  - \(|6 < Q < 17|\)

- CMS: MS
  - \(arXiv:1305.0491\)
  - \(|19/|fb|\)
  - ATLAS: MDT+RPC
    - \(arXiv:1106.4495\)
    - \(|37/pb|\)

- CMS: CALO
  - \(arXiv:1501.05603\)
  - ATLAS: CALO
    - \(arXiv:1310.6584\)

Note: \(^*\) apply to \(g_d \neq 0\)

12/11/2015 - Searches for HSCP at the LHC
Loic.Quertenmont@cern.ch
Selected Results: \textbf{R-Hadrons (0$\rightarrow$±)}

- **Challenges:**
  - Invisible in the tracker
  - Worse pT resolution (due to coarser hit position in the MS)
  - High cosmic backgrounds (also out-of-time)

- **Solutions:**
  - Dedicated trigger (stand alone muons without inner track matching)
  - Tight Cosmic Veto
  - Muon TOF must be compatible with IP collisions

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**Background (ABCD)**

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Limits vs fraction of Gluino balls

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12/11/2015 - Searches for HSCP at the LHC

Loic.Quertenmont@cern.ch
Results Recasting

• Despite the important number of HSCP analyses and physics cases studies, we clearly don’t cover the entire space of possibilities
  - Interaction with matter
  - (R-)hadronization (f gluino balls) or bouding (quirks, dyons)
  - Production mechanism → kinematics
  - Life time

• Some analyses provide signal acceptance for
  - Very basic assumptions (e.g. DY-like production)
  - Or even sometimes for a set of simplified models

• But, still the possibilities are so many that it is difficult to cover every models and/or ingredients for usual Simplified Model recasting.

RECASTING ENGENEERING NEEDED
CMS HSCP recasting (first attempt)

- In CMS, we proposed a new technique to estimate the signal acceptance from generator level information (no assumption on kinematics, mass split, etc.)
- The technique is valid for any number of lepton-like HSCP per event
  - This was a first attempt that could in principle be generalized to Rhadron...

\[ e = \frac{1}{N} \sum_i^N P^{\text{on}}(k_i^1, k_i^2, \ldots, k_i^M) \times P^{\text{off}}(M_{\text{req.}}, k_i^1, k_i^2, \ldots, k_i^M), \]

- Efficiency is decomposed event by event on « online » and « offline » components that only depend on the long-lived particle kinematics:

\[ P^{\text{on}}(k_i^1, k_i^2) = P^{\text{on}}(k_i^1) + P^{\text{on}}(k_i^2) - P^{\text{on}}(k_i^1) \times P^{\text{on}}(k_i^2) \]
\[ P^{\text{off}}(M_{\text{req.}}, k_i^1, k_i^2) = P^{\text{off}}(M_{\text{req.}}, k_i^1) + P^{\text{off}}(M_{\text{req.}}, k_i^2) - P^{\text{off}}(M_{\text{req.}}, k_i^1) \times P^{\text{off}}(M_{\text{req.}}, k_i^2) \]

- This allows to consider cases where one of the HSCP trigger the event and the second one pass the offline selection.

\[ P^{\text{on}}(k) \] and \[ P^{\text{off}}(M_{\text{req.}}, k) \] are evaluated using a full simulation of the detector

The functions only depend on the kinematic (\(\eta, \beta, p_T\)) of an individual long-lived particle. These parameterizations are publicly available (hep-data).

- Recipe to account for HSCP isolation and/or shorter lifetimes are also provided
• HSCP lifetime and isolation can also be taken into account.

• The technique was used to recast CMS results in the context of two models:
  • Both considering cases of « finite lifetime »

---

**pMSSM**

<table>
<thead>
<tr>
<th>Points in pMSSM LHC sub-space (M ≤ 3 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowed</td>
</tr>
<tr>
<td>Excluded</td>
</tr>
<tr>
<td>HSCP</td>
</tr>
<tr>
<td>Prompt SUSY (cτ &lt; 10 mm)</td>
</tr>
</tbody>
</table>

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**AMSB**

<table>
<thead>
<tr>
<th>Frac. excluded</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15 -10 -5 0 5 10 15 20</td>
</tr>
<tr>
<td>1 0.8 0.6 0.4 0.2 0.1</td>
</tr>
</tbody>
</table>

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1. Idea of sModels is to decompose a model in a sum of simplified models (across channels) and compare the acceptance of each leg to exp. results.

\[ \sigma_{\text{eff}} = \sum_i (\sigma BR \epsilon_i) \]

2. This was recently extended to long-lived branches. Acceptance for 8 different simplified models were computed using the CMS recasting techniques:

- mProd, mInt and mHSCP were all varied from 50GeV to 3TeV.

3. Limits were set on CMSSM stau co-annihilation by combining MET and HSCP signatures.

arXiv:1509.00473
Conclusion

• Both ATLAS and CMS have tracked down HSCP using many different techniques
  • Electric charge form e/3 to 60e
  • Magnetic charge from 0.5g\textsubscript{D} to 1.5g\textsubscript{D}
  • Colour charge (stop, sbottom, gluino)
    • Including a couple of models for hadronization and interaction with matter
  • Lifetimes from O(10\textsuperscript{-9}) ns to infinity (O(10\textsuperscript{8}) for stopped)

• So far, no signs of HSCP in 7 or 8 TeV LHC data
  • But still many possible places to hide them…
  • 13TeV door is just opening now…

• Still… only a limited set of models / physics cases were considered
  • Work on reinterpretation/recasting technique started…
  • But more work/ideas are needed
One more for the Zoo... soon...

More to come at 13TeV...

...Stay tuned!

HSCP
He is a bit slow but really long-lived. And yet to be discovered...
Backups
Disappearing track & pMSSM

Disappearing track partially filling the gap on LL charginos in pMSSM

But still ~50% to exclude there